Northern Environmental Education Development

Vatnajökull National Park: Geology and Geodynamics

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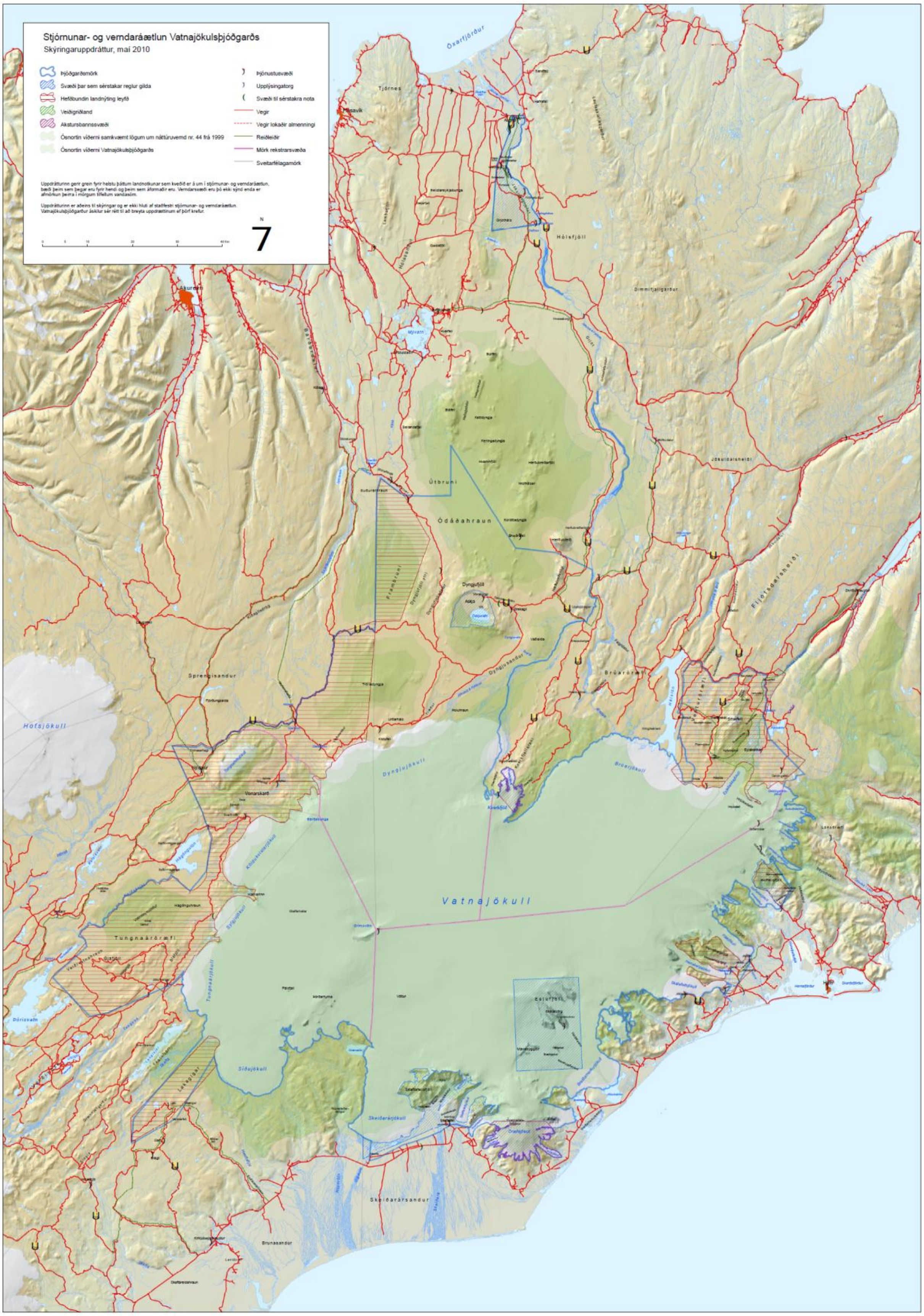

Map of Vatnajökull National Park (as of May 2010) showing its borders and main administrative areas (VNP Management Plan, 2010).

CHAPTERS

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Introduction

Vatnajökull National Park was fomally established in June 2008. It is the largest national park in Europe, roughly 13.500 km^2 in size, covering about 13% of the surface area of Iceland. The main objectives of the park are to conserve landscapes, biology, geological formation and cultural heritage and to enable the public to experience and enjoy its nature and history. The park contains extraordinary varieties of landscapes formed by interaction of fire and ice, glacial lakes, geothermal areas, ice-caves, active and extinct volcanoes, alpine landscapes, and much more (for further information, see http://www.vatnajokulsthjodgardur.is/english) .

Geodiversity has become an important part of nature conservation, just as biological diveristy. Geodiversity has been defined in several ways. Collectively, the diversity is based on bedrock, sediments, landscapes, soil, minerology, fossils, along with geological and geophysical processes that build and erode the earth´s crust. Geodiversity within Vatnajökull National park is very high. The border of the park is not always defined naturally by landscape, since ownership and other land-use practices have affected which areas belong to the park. Although some natural phenomena discussed in this review are at present outside the park‘s boundaries, they will nevertheless be included here, due to their geological importance and likelihood of becoming part of the park in the near future, or at least being defined as belonging to its peripheral zone.

In this report, we will give an overview of the geology and geodynamics that have shaped Vatnajökull National Park. We refer to a geo-reference list compiled by the Hornafjörður Rural Research Centre and the national park for further information (see www.need.is).

Landscapes

Alho, P et al. 2003 & 2005; Guðmundsson, M.T. 2006; Liccardi, J. et al. 2007; Björnsson, H. 2009; Board of Vatnajökull National Park 2010; Carrivick et al., 2004; Baldursson et al., 200

Fire and ice in the volcanic zone

Previous and ongoing interaction of fire and ice has had the greatest impact on the landscapes of Vatnajökull National Park, from the south coast to the north coast. The geological history and landscapes of the park are diverse and unique. Jökulhlaups (outburst floods from glaciers) are common, caused by sub-glacial eruptions or bursting of geothermal subglacial lakes. Some have drained to the south below Skeiðarárjökull and Tungnaárjökull and formed the greatest sandurs (outwash plains) in Iceland, and entered Jökulsá á Fjöllum to the north and carved out the largest canyon. During glaciation, table mountains, or hyaloclastite ridges were formed in subglacial eruptions and these are also formed in modern eruptions in Vatnajökull. The hyaloclastite landscapes are very characteristic of Iceland and have not formed in recent geological time elsewhere on Earth.

The volcanic zone north of Vatnajökull is covered by Holocene lavas, with numerous hyaloclastite mountains and jökulhlaup and wind-blown deposits smoothing the rugged landscape. The sandy lava desert north of Vatnajökull (Ódáðahraun) is wide open and difficult to traverse, and was in the past believed to be the home of many outlaws and ghosts. On the southern edge of Vatnajökull, alpine glaciers carve deep valleys reaching 200-300 m below sea level. The ice-capped Öræfajökull volcano (highest mountain in Iceland, 2.110 m above sea level) has erupted in historical times and feeds several of these alpine outlet glaciers. Nowhere in Iceland are as many glacial lakes as in Austur-Skaftafellssýsla. The large active sandurs of Skeiðarárjökull (ca. 1.000 km$^{2)}$ and Breiðamerkurjökull are unique in the world.

Table 1. Comparison of areas in the world with interaction of fire and ice (from Guðmundsson, M.T. 2006).

geological features	table mountains	hyaloclastite ridges	lava fields	shield volcano	sandur	large volcanoes	large canyons	large glaciers	subglacial volcanoes	jökulhlaups
location										
NW Canada	x					x				
Kamchatka peninsula						x	x		x	x
Alaska					x	x	x	x	x	x
NW US					x		x		x	x
Andes mountains			x		x	x			x	x
North island of NZ						x			x	x
Antarctica	x					x		x	x	x
catchment area of Jökulsá á Fjöllum	x	x	x	x	x	x	x	x	x	x

THE SOUTHEAST COAST

The southeast coast along the southern border of Vatnajökull National Park has some of the most magnificent views to be found in Iceland; alpine glaciers, black beaches, glacial lakes, ancient sea cliffs, rockfalls and landslides. The cultivated lowlands of Öræfi, Suðursveit and Mýrar counties were originally sandur plains, built from debris transported by glacial rivers. Alpine glaciers and landscape dominate the scene in Skaftafell and along the flanks of Öræfajökull. The mountains are incised by steep sided valleys carved out by descending outlet or valley glaciers. From some valleys the glaciers have disappeared whereas others are still at work, like the large valley glaciers Skálafellsjökull, Heinabergsjökull and Fláajökull.

Marine erosion

Wave motion is a very effective tool of erosion, and its effects are greatest in shallow water, particularly along the coast. The mountainous areas southwest, south and southeast of Vatnajökull ice cap delineate these ancient sea cliffs. Former marine terraces witnessing the higher marine limit can be found in the area. They were formed as the land adjusted isostatically after the weight of the last Pleistocene ice sheet was removed and the sea flooded the lowland because of the slow uplift of the land and the world wide rise of sea level.


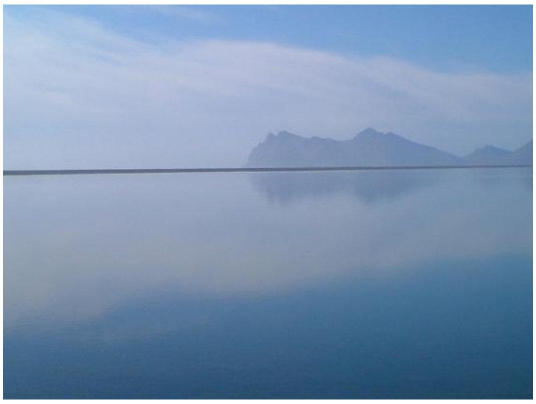

Figure 1. **to the left:** Previous ***sjávarhamrar*** at Foss á Síðu west of Skeiðarársandur (photo: www.klaustur.is). **Figure 2. on the right:** Lónsfjörður southeast of Vatnajökull ice cap (photo: www.trekearth.com)

Sand and gravel are transported along the coast in the same direction as the wind and ocean currents. In vigorous wave action the gravel is often carried inland to build up beach ridges. Through time bays and fjords have become filled by fluvial and marine sediments closing them off with a spit or bay barrier. Inland lagoons are formed, e.g. Lónsfjörður and Hornafjörður.

Rockfall and landslides

The transport of rock always depends on the Earth‘s gravity. Movements can be slow as in the case of solifluction or very rapid for rockfall or landslides. A rockfall refers to quantities of rock falling freely from a cliff face. A rockfall is a fragment of rock (a block) detached by sliding, toppling, or faulting, which falls along a vertical or sub-vertical cliff. This occurs mainly when ice expansion and differential heating loosen rocks so that they fall. Through time, the slopes become covered in screes. Huge screes occur on the slopes of Vestrahorn and Eystrahorn in Lón ,southeast of Vatnajökull ice cap.

Figure 3. to the left: Vestrahorn (photo: Hrafnhildur Hannesdóttir). **Figure 4. to the right:** Hvalnes in Lón (photo: www.flickr.com).

Landslides are piles of broken rocks formed when an entire mountain side collapses in a single event. In Iceland landslides have occurred mainly in the Tertiary basalt areas where glaciers have steepened slopes or on higher cliffs formed by marine erosion. Landslides leave a visible scar in the mountain side and debris at the bottom of the slope. One of the most spectacular landslides is the one below Lómagnúpur west of Skeiðarársandur.

Roots of ancient volcanoes

The countryside of Lón was once the boiling hot roots of three volcanoes, located 2-3 km below the surface. Erosion has removed much of the extrusive rock and exposed deeper intrusions. The larger gabbro intrusions of Viðborðsfjall, Vestrahorn and Eystrahorn represent ancient basaltic magma chambers that provided the fuel for some of the Tertiary central volcanoes in the region. Some exposed granophyre intrusions can also be seen, e.g. at Ketillaugarfjall, Slaufrudalur, Vestrahorn and Eystrahorn. Typically they are situated a little higher in the stratigraphy and above the gabbro intrusions. The Álftafjörður volcano includes the spectacular Mælifell caldera which is a subsidiary structure on the southern margin of the main caldera of the Álftafjörður volcano. The Mælifell caldera is 2 km in diameter and is made up of welded tuffs, agglomerates and tuffaceous sediments, along with rhyolite and andesite lava flows. The light coloured mountain cluster of Kjós is the root of the Skaftafell central volcano, which is very rich in rhyolite with basaltic intrusions.

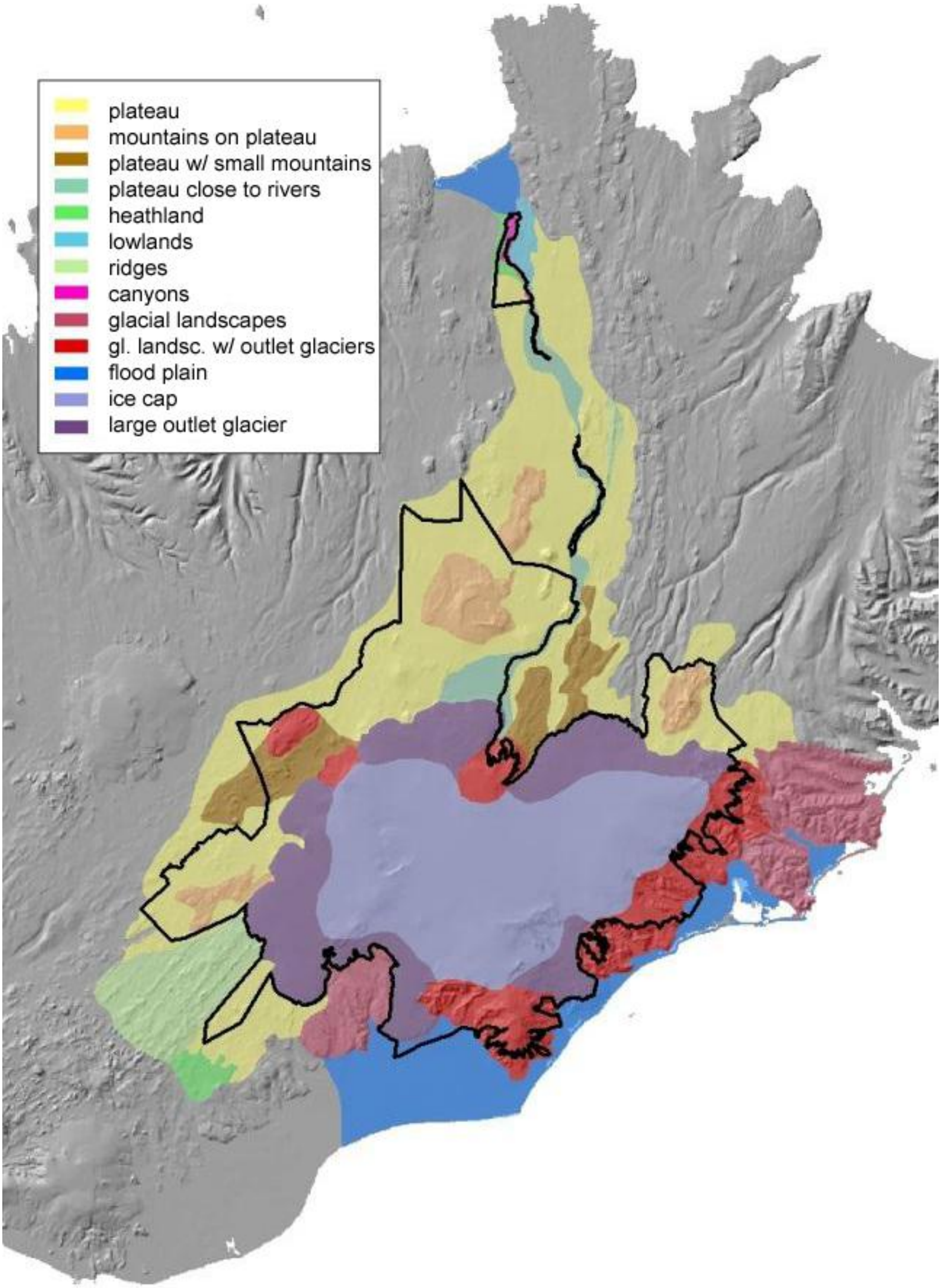

Figure 5. Main landscape features of the national park (VNP Management Plan, 2010).

Vatnajökull ice cap

Björnsson, 1988, 1992, 2009; Björnsson et al., 2003, 2004, 2008; Aðalgeirsdóttir et al. 2006; Board of Vatnajökull National Park 2010; Institute of Earth Sciences; Þórarinsson, 1974;Guðmundsson et al., 2002;

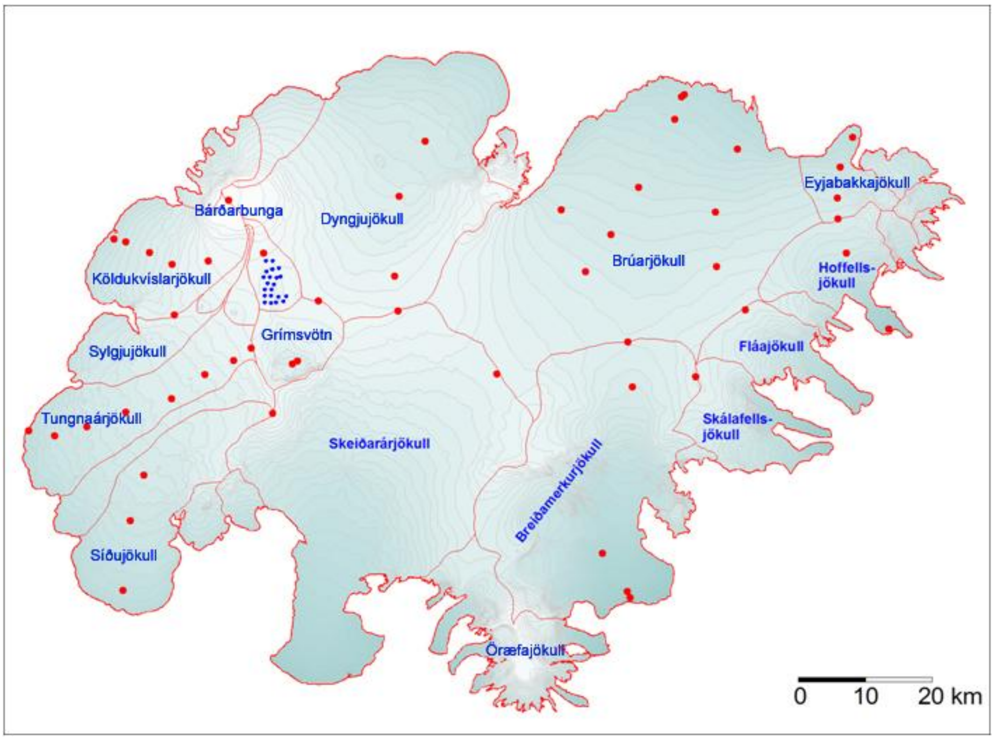

Figure 6. Ice divides (red lines) of Vatnajökull ice cap and individual outlet glaciers. Red dots indicated locations of mass-balance measurements.

Vatnajökull is the largest ice cap outside the polar regions, around 8,000 km^2 in size. It is a temperate glacier (as are all Icelandic glaciers), nowhere frozen to the bedrock like the polar ice cap. Its mean thickness is about 400 m and maximum thickness close to 1 km. The ice cap´s mean altitude is 1300 m, the maximum more than 2100 m, and the lowest point at the glacier base is at 300 m below sea level, underneath Breiðamerkurjökull. Ice drains several domes at 1400-2000 m elevation, with margins at 600-800 m on the western and northeastern margin versus 50-100 m on the southern side.

Glaciers in Iceland owe their existence to a maritime climate and they are located in mountainous areas where precipitation is highest. The glaciers are sensitive to climate change and respond rapidly by advancing or retreating. Almost every type of glacier is found in Iceland, from cirque glaciers to large ice caps, including alpine glaciers draining from Öræfajökull and ice-covered volcanoes such as Grímsvötn. The glaciers in Iceland are all temperate, which means they are at the melting point. The snowline, the altitude at which snow survives summer melting, varies from 750 m in the Westfjords to around 1700 m north of Vatnajökull ice cap. In central Iceland and at the southern edge of Vatnajökull the snowline is around 1100-1200 m elevation. Glaciers in Iceland cover approximately 10% of the country and 60% of them are located in the volcanic zone and cover geothermal areas and active or extinct volcanoes.

Surge-type glaciers are common in Iceland, these are characterized by sudden advance of the glacier tongue, due to ice being transported quickly from the accumulation area to the ablation area. The glacier becomes heavily crevassed and water gushes out from the glacier

margin. The largest outlet glaciers are Síðujökull, Tungnaárjökull and Köldukvíslarjökull on the western side, Dyngjujökull and Brúarjökull to the north, and Breiðamerkurjökull and Skeiðarárjökull on the southern edge. They have all surged with a reoccurence of a couple of decades.

Some of the most active volcanoes in Iceland are subglacial, such as Grímsvötn. Glacier outburst floods (called jökulhlaups) drain regularly from six subglacial geothermal areas and from fifteen ice-dammed lakes. Jökulhlaups affect landscapes, damage vegetation, threathen lives, infrastructure and hydroelectrical power plants on glacial rivers. They erode large canyons and transport and deposit sediments (ranging in size from sand to boulders) over outwash plains. Jökulhlaups have become smaller and more frequent as the glaciers have retreated. Some thousands of years ago catastrophic jökulhlaups (presumably originating in Bárðarbunga) carved out Jökulsárgljúfur and Ásbyrgi in the north.

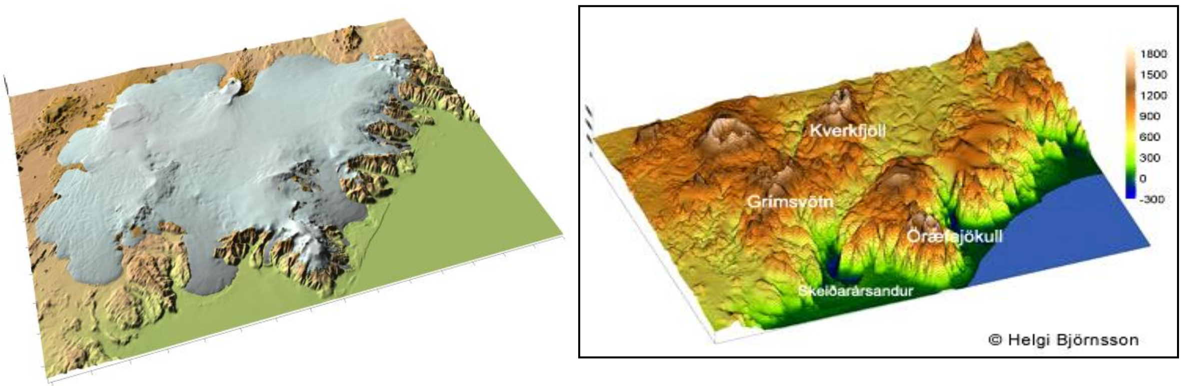

Figure 7. Elevation map of Vatnajökull ice cap from the southwest (to the left) and the bedrock topography of the same area (Earth Science Institute).

The landscape beneath the largest glaciers has been uncovered through radio-echo sounding measurements, showing extinct volcanoes and meltwater channels below hundreds of meters of ice. Future changes of glacial rivers are foreseen due to the rapid glacial retreat. Knowledge about the bedrock topography is important for prediction of future changes of glacial runoff and glacial topography. Information on the location of subglacial volcanoes and subglacial geothermal lakes, and the routes of jökulhlaups is valuable for road construction and civil defence actions. The radio-echo sounding measurements provide information on tephra layers in the ice, and they have been analyzed from ice cores and samples from the edge of the glacier. They provide information on the age of the ice and its accumulation patterns. The oldest ice recovered from Vatnajökull was formed prior to a volcanic eruption dated to 1150. The volcanic history of Vatnajökull has been read from the tephra layers, since the time of settlement in Iceland (ca. 870 A.D.) at least 80 subglacial volcanic eruptions have taken place in Vatnajökull. Seven central volcanoes are below the Vatnajökull ice cap; Bárðarbunga, Hamarinn, Grímsvötn, Þórðarhyrna, Kverkfjöll, Esjufjöll and Öræfajökull. They are of various types and of different activity.

Evidence indicates that the remains of the ice sheet of the last glacial period disappeared 6,000-8,000 of years ago. The largest glaciers in Iceland formed in a colder climate than today, presumably during a colder and wetter period 4,000-5,000 years ago. If today´s glaciers would disappear only small glacier would form on the highest peaks above the current snow line. A recent cold period called the Little Ice Age lasted from approximately 1300 until 1900, during which time glaciers in Iceland advanced and some reached their maximum extent since end of the last glacial period 10,000 years ago. During this cold period some outlet glaciers of Vatnajökull advanced up to 10-15 km from their

position at settlement times. In front of the outlet glaciers are sandy outwash plains (called sandur), witnessing their great erosional power and the sediment transport of the glacial rivers. Among them is Skeiðarársandur, which is the largest active sandur in the world. Seismic measurements in the area indicate 100 m thick sediment deposits near the glacier margin, thickening to 250 m at the coast. The sediments have piled up during the last 10,000 years from jökulhlaups and sediment lain glacial rivers.

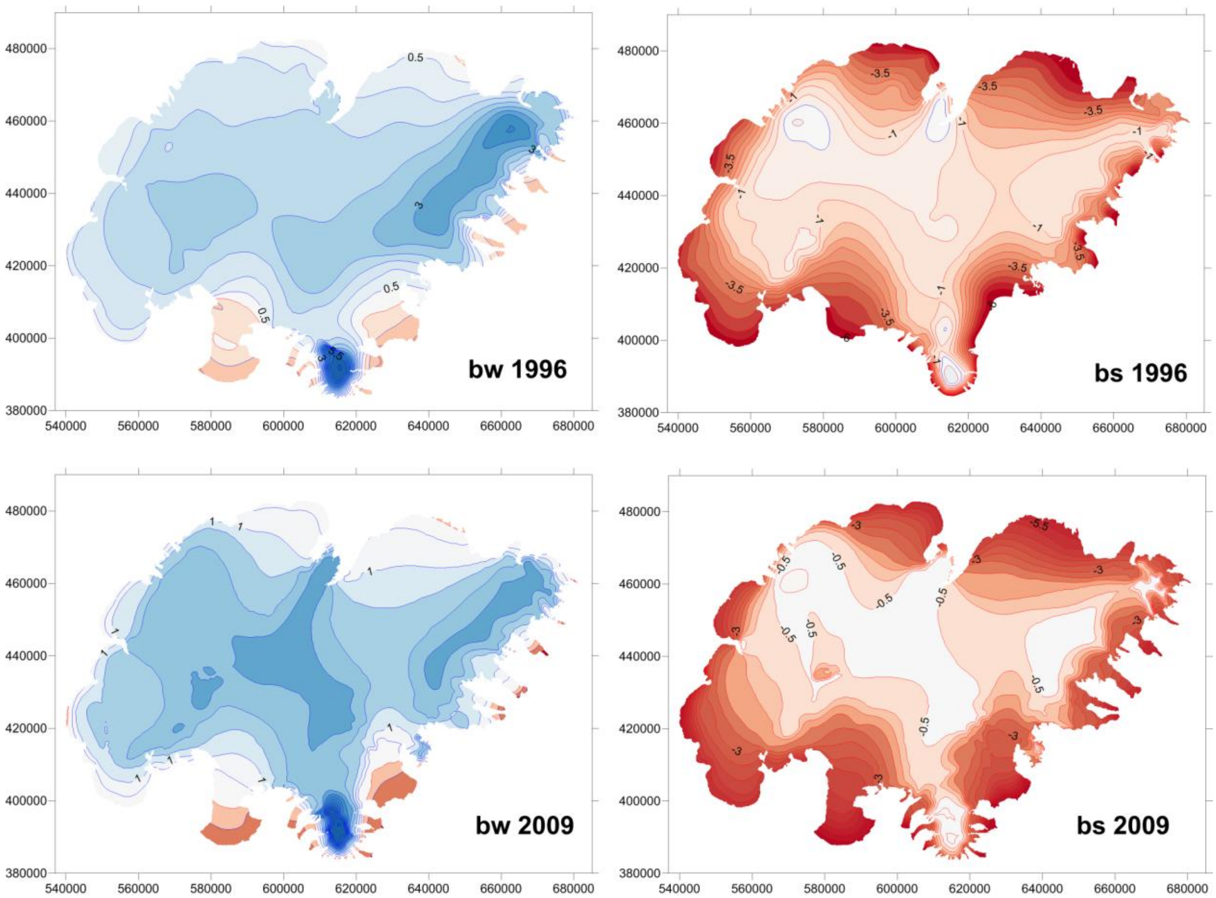

Figure 8. The winter and summer balance of Vatnajökull in 1996 and 2009 (Earth Science Institute).

Glaciers in Iceland have retreated in the 20th and 21st century. Rapid decrease took place during the warm period 1930-1960. Most glaciers advanced in the years 1970-1995 due to a colder climate, however, in the last 15 years almost all glaciers have retreated and thinned at an unprecedented rate. Vatnajökull has decreased by about 10% in volume since the end of the 19th century, whereof 3% were lost in the last 10 years or so. Future climate scenarios indicate that the large ice caps will almost disappear in 150-200 years, leaving only small glaciers on the highest peaks. Glacial lakes have formed in front of many southern outlet glaciers of Vatnajökull, due to 100-300 m deep channels below the glaciers. They will increase in size as well as the Jökulsárlón glacial lagoon, which has increased rapidly in size since the 1990´s. In the warming climate of the last 15 years Vatnajökull has lost about 1 m of its thickness each year (evenly distributed over the whole area), the firn line has risen 200-400 m and the accumulation areas of the outlet glaciers is just half of what they need to be for the glaciers to remain unchanged. Major rapid environmental changes are foreseen in the warming climate. Rivers will change their course and disappear. Vegetation, infrastructure,

land-use management, hydro-power plants, volcanic activity and land uplift will all be affected by retreating glaciers.

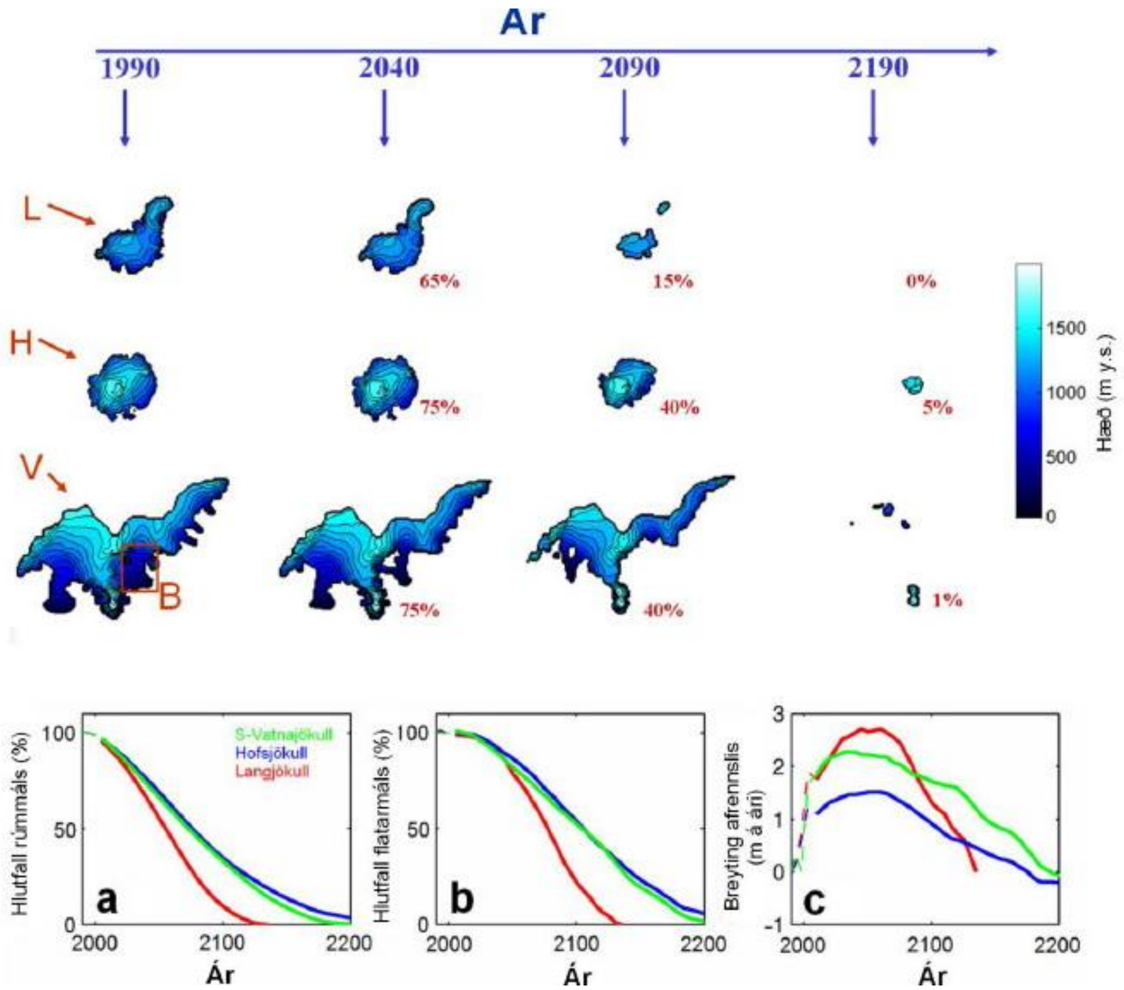

Figure 9. Retreating glaciers given certain future climatological models, L=Langjökull ice cap, H=Hoffellsjökull, V=southern Vatnajökull. Volume, area and runo changes during the same time period (from Aðalgeirsdóttir et al., 2006).

Evidence of the glacier‘s larger extent in previous times and its current retreat is found at the glacier margin. Glacial moraines, trimlines, shorelines of previous ice-dammed lakes, flutes, and other geomorphological evidence are indicative of the greater extent of Vatnajökull´s outlet glaciers. Many of them reached their maximum extent during the Little Ice Age during the latter part of the 19th century, others have left behind moraines thousands of years old outside the Little Icea age limit. Glacial landforms are particularly vulnerable for off-road driving practices and mining, and therefore need special protection.

Some of the largest glacial rivers originate in Vatnajökull ice cap. Until the beginning of the 20th century the glacial rivers were spread out on the sandur, but as the glaciers retreated frontal lakes started to form and the glacial runoff entered these lakes. They deposit the sediments and the erosional power of the glacial rivers decreases, and the glacial rivers

follow channels instead of spreading out over the sandur. Dishcarge of glacial rivers is dependent on air temperature, hence seasonal variations occurs as diurnal. The sediment rich water give them a milky appearance, and increases their erosive power.

Figure 10. The canyon of Jökulsá á Fjöllum with Hafragilsfoss waterfall.

Glacially eroded rock hills are smooth, striated and gently sloped on the side facing the direction of the ice flow (where the pressure is greatest). The lee side is steep and craggy. Whalebacks are very common in broad valleys and in the lowlands in front of the outlet glaciers. The whalebacks are often with hollows occupied by tarns or lakes between.

Figure 11. to the left: Whalebacks of Skálafellsjökull (photo: Andreas Zöhrer). **Figure 12 to the right:** Moraines of Skálafellsjökull (photo: Hrafnhildur Hannesdóttir).

Glaciers deposit sediments in the ablation area or at the snout of the glacier. A large amount of debris is carried along in the basal layer as ground moraine. End moraines are pushed up when the glacier is advancing or are deposited from medial or lateral moraines. Individual slabs of the retreating glacier often remain in till or fluvial deposits. When the ice melts a depression is formed which becomes filled with water to form kettle holes. These features are common in the sandur areas of southern Iceland. Meltwater, which flows in channels on, in or underneath the glacier deposits its sediment loads in the same way as other rivers. As the glacier melts, long sinuous ridges of sand and gravel called eskers become visible.

Geodynamics (volcanism, rifting and geothermal heat)

Þórðarson et al. 2002; Guðmundsson, 2006; Þórðarson & Höskuldsson, 2008; Þórðarson & Larsen 2007; Einarsson, 2008; Arnórsson et al. 2008; Guðmundsson & Högnadóttir, 2009; Jónasson & Einarsson, 2009; Friedman et al., 1972; Einarsson, 1991; Þorsteinsson et al., 2007

Iceland is one of the most active and productive terrestrial volcanic regions on Earth, with an eruption frequency of >20 events/century. The Iceland hotspot has a pronounced effect on the appearance and structure of the plate boundary between the North America and Eurasia Plates that cross the island. High volcanic productivity over the mantle plume beneath Iceland produces a thick crust. Iceland is situated at the junction of two large submarines physiographic structures, the Mid-Atlantic Ridge and the Greenland–Iceland–Faeroe Ridge. Active spreading and eruption of magma take place at the plate boundary. The plate boundary is delineated by a series of faults and volcanoes, which together form a characteristic ridge–like structure. Current volcanism in Iceland results from superposition of the spreading plate boundary over the Iceland mantle plume, as well as from the relative motion of these two structures. The Iceland Basalt Plateau rises more than 3,000 m above the surrounding sea floor, has a crustal thickness of 10-14 km and covers about 350,000 km^2. The neovolcanic zones delineate 15-50 km wide belts of active faulting and volcanism. The neovolcanic zones are further divided into volcanic systems, which can be viewed as the principal geological structure in Iceland. 30 active volcanic systems are found in the neovolcanic zones. The volcanic systems are characterized by conspicuous volcano tectonic architecture that features a fissure (dyke) swarm or a central volcano or both and has a typical lifetime of 0.5–1.5 million years. The fissure swarms of each system are elongate structures that normally are aligned sub-parallel to the axis of the hosting volcanic zone. The central volcano, when present, is the focal point of eruptive activity and typically the largest edifice within each system. The cluster of volcanic and tectonic surface structures are used to define the volcanic systems.

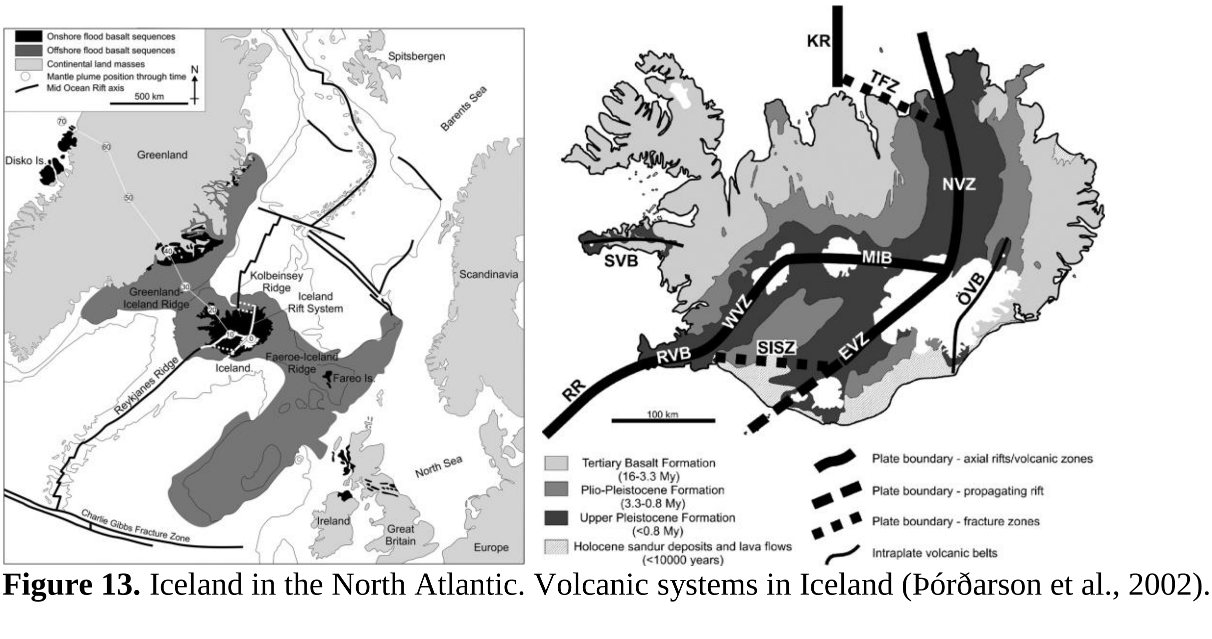

Figure 13. Iceland in the North Atlantic. Volcanic systems in Iceland (Þórðarson et al., 2002).

Five volcanic systems are found in the North Volcanic Zone (NVZ) which is joined by the Mid-Iceland Belt (MIB) and linked to the Mid-Atlantic Ridge system by the Tjörnes Fracture Zone in the North. The Eastern Volcanic Zone (EVZ) was responsible for 80% of volcanic activity during the Holocene and contains 8 volcanic systems. This rift zone extends from the eastern end of the South Iceland Seismic Zone to about 100 km to the NE, where it

joins the NVZ and the MIB. The central volcanoes of the EVZ are to a large extent covered by the Vatnajökull glacier. In East-Iceland there is also an active intraplate volcanic belt; the Öræfi Volcanic Belt, situated to the east of the plume centre and the current plate margins and presents an embryonic rift. This Volcanic Belt shows a possible move of entire Iceland to the west and indicates therefore another jump in the spreading axis across Iceland.

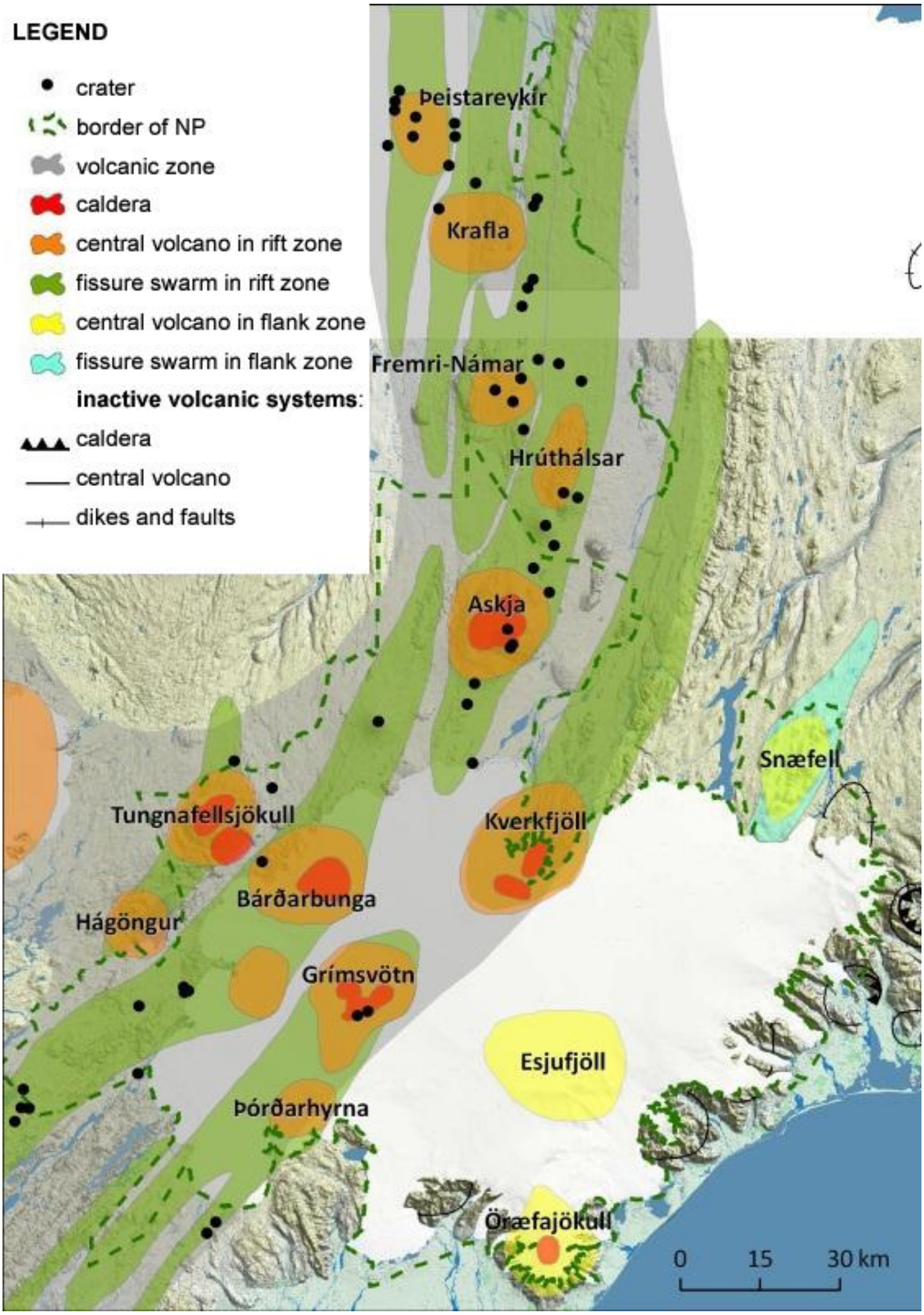

Figure 14. Volcanic systems inside the national park (VNP Management Plan, 2010).

Geothermal areas in Iceland are divided into high and low temperature areas. High-temperature systems are located within the volcanic zones and their heat sources are high-level magma intrusions. Most high-temperature fields lie astride active fissure swarms, where they intersect the lithosphere plate boundary. Within Vatnajökull National Park are several geothermal areas associated with the central volcanoes, as well as subglacial geothermal areas. Here we mention a few of these.

Skaftárkatlar

Skaftárkatlar (the Skaftá cauldrons) are two subglacial lakes in western Vatnajökull, each about 1-2 km in diameter. Meltwater accumulates continuously due to geothermal heat at the base of the glacier. They drain every 2-3 years in jökulhlaups, which enter river Skaftá. About 40 jökulhlaups are known to have stemmed from the cauldrons during the last 50 years. Between jökulhlaups water accumulates in the lakes and they rise by 70-100 m.

Figure 15. to the left: One of the Skaftá cauldrons, with Grímsvötn, Grímsfjall and Öræfajökull in the background (photo: Matthew Roberts). **Figure 16. to the right:** The geothermal area in Kverkfjöll, Galtarlón in the foreground (photo: www.vinirvatnajokuls.is).

Grímsvötn

The geothermal system of Grímsvötn is one of the most powerful in the world, with a heat loss of 2000-4000 MW. The geothermal system melts ice and water accumulates in the 600 m deep caldera lake. Jökulhlaups in Skeiðará originate in the subglacial lake, which is sealed by a floating ice shelf. The ice melting gradually increases the volume of the lake. When the surface of the lake reaches a critical level, the water is sufficient to open a 50 km long subglacial tunnel to the edge of Skeiðararjökull. When this happens, up to 80% of the lake is drained in a jökulhlaup that typically lasts for one or three weeks. Normally the Grímsvötn caldera lake is drained every five to ten years.

Kverkfjöll

The geothermal area of Kverkfjöll is in Hveradalur, a small valley at 1600-1700 m elevation, and is thought to be among the most powerful in Iceland. The geothermal heat has produced two lakes, Gengissig, a lake close to the hut of the Glaciological society in Kverkfjöll and Galtarlón in upper Hveradalur. Jökulhlaups, originating in Gengissig (and possibly Galtarlón) flow below Kverkjökull and into river Volga, which flows into Jökulsá á Fjöllum. Hyaloclastite formations characterize the geology of the area, but lavas are also present. The highest geothermal activity is at the front of Hveradalur and it follows the faults.

Bedrock

Einarsson, 1994; Þórðarson et al,. 2002; Sæmundsson et al., 2002; Geirsdóttir 2007

Iceland consists mainly of volcanic (igneous) rocks and is geologically very young. It has been built up during the Miocene, Pliocene and Quaternary. The geological formations are divided into four main groups: the oldest one is the Tertiary Basalt Formation, then the Grey Basalt Formation, then the Hyaloclastite (Móberg) Formation, and finally the youngest formation which consists of unconsolidated or poorly hardened beds (like till or glaciofluvial deposits) (Einarsson, 1994). These formations are all found within Vatnajökull National Park (figure 4).

Iceland is entirely composed of lava flows and eruptive hyaloclastites, with widespread sedimentary areas located in between. Igneous intrusions are quite common in the roots of inactive central volcanoes in Southeast-Iceland (e.g. Lónsöræfi). The Tertiary basalt formation in Iceland is mainly composed of basaltic lava flows. Most eruptions occurred in eruptive fissures while others occurred in central volcanoes. Individual volcanoes are now seldom found as the crater walls had been worn down before the next lava buried them. But dikes are still visible, they are related to the single lava flows and are the most common intrusions in the Tertiary Basalt Formation. Also quite common are amygdules in this formation, particularly zeolites, calcite and quartz minerals.

Rock formations from the Pleistocene (Grey Basalt and Móberg Formation) overlay the Tertiary Basalt Formation on both sides. Because of the different climate the Pleistocene formations differ from the tertiary basalt. The red sediments which are typical of the Tertiary Basalt Formation disappear and are replaced by glacial tillites and yellow or brown hardened silt and sandstones. Sediments in Grey Basalt and Móberg Formations are much thicker than in the Tertiary Basalt since fluvial and glacial erosion were very active during the late Pliocene and Pleistocene. The sediments are either fluvial, lake or marine in origin and formed mainly during interglacial periods, or glacial till which was deposited by the glacier during the glacial period.

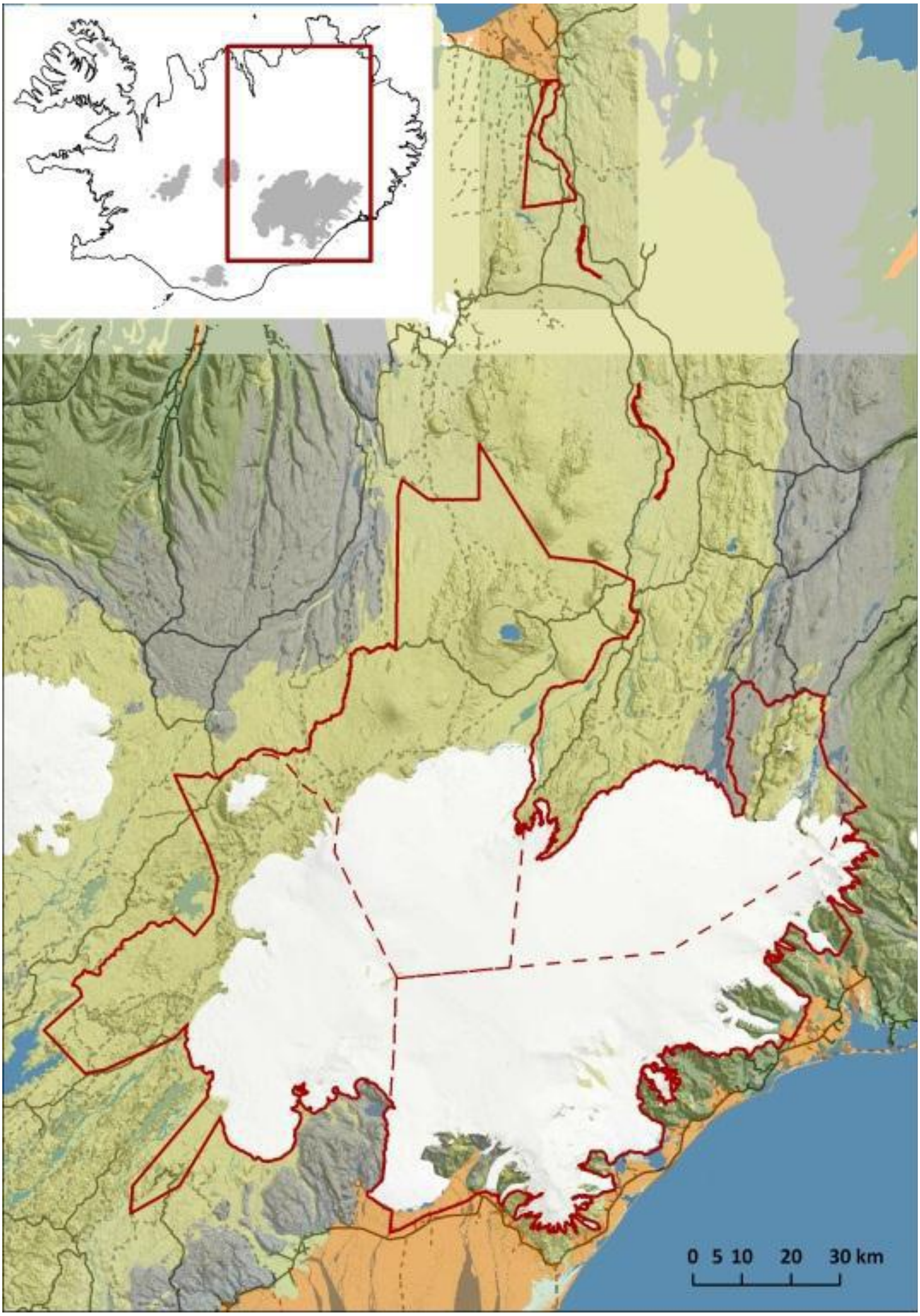

Figure 17. Bedrok formations of Vatnajökull National Park. Green: oldest Tertiary basalt (16-3.3 million years old). Bluegrey: younger Grey basalt /3.3-0.8 million years old). Yellow: hyaloclastite (800,000-15,000 years old). Orange: Holocene sediments (last 10,000 years) (VNP Management Plan, 2010).

Table 2. Bedrock formations of Vatnajökull National Park.

Bedrock formation	Area km^2
Basic and intermediate hyaloclastite, pillow lava and associated sediments. Upper Pleistocene, younger than 0.8 m.y.	1088,91
Basic and intermediate lavas. Postglacial, prehistoric, older than 1100 years.	664,91
Basic and intermediate extrusive rocks with intercalated sediments. Upper Pliocene and Lower Pleistocene, 0.8 - 3.3 m.y.	265,32
Basic and intermediate interglacial and supraglacial lavas with intercalated sediments. Upper Pleistocene, younger than 0.8 m.y.	254,69
Basic and intermediate lavas. Postglacial, historic, younger than 1100 years.	177,46
Basic and intermediate extrusive rocks with intercalated sediments. Upper Tertiary, older than 3.3 m.y.	133,78
Acid extrusives. Tertiary and Pleistocene, older than 11000 years.	129,15
Holocene sediments	79,01
Basic and intermediate intrusions, gabbro, dolerite and diorite	0,78
Acid intrusions , rhyolite, granophyre and granite	0,44

Climate

www.vedur.is; Guðmundsson, 2000; http://www.vatnajokulsthjodgardur.is; Preusser, 1976; www3.hi.is/~oi/; Bergþórsson, 2004, portal.belgingur.is

Iceland is located at oceanographic and atmospheric boundaries of the North Atlantic. The climate is temperate and maritime, summers are cool and winters mild. The ocean currents have a big influence on temperature and precipitation. The Irminger current flows in a clockwise direction along the south and west, whereas the East Iceland Current, the cold ocean current, flows along the north-east and east coasts. The winter sea temperatures around the island are higher than the air temperatures and even in the summer they are sometimes higher than the air temperature. There is a stark difference between various parts of the country. In general, the mean temperature is higher in the south because of the higher temperatures during the winter months. The climates on the north and south sides of Vatnajökull are very different, exhibiting both extremes of Icelandic weather, i.e. the maritime climate of the south coast and the continental climate of the deserts of Ódáðahraun. We will mainly focus on the current climate, but few areas in Iceland have been affected to the same extent by the climate fluctuations of the last few hundred years. During the Little Ice Age (1300-1900) the climate grew colder and glaciers expanded to an unprecedented size in historical times.

Precipitation

The pattern of precipitation in Iceland reflects the passage of atmospheric low pressure cyclones across the North Atlantic Ocean from south-westerly directions, exposing the south coast to heavy precipitation. Precipitation is the highest in Iceland on the southern side of the Vatnajökull ice cap, measured at Kvísker, from 1000-4000 mm/year. Higher up on the ice-covered Öræfajökull, volcano borehole measurements indicate 7500 mm/year of precipitation, most of which falls as snow. On the northern side of Vatnajökull, desert like conditions are characteristic for the area due to the rain-shadow. The lowest amount of precipitation (350-450 mm/year) is measured at … (***hvaða veðurstöð?)***, with increasing values towards the coast.

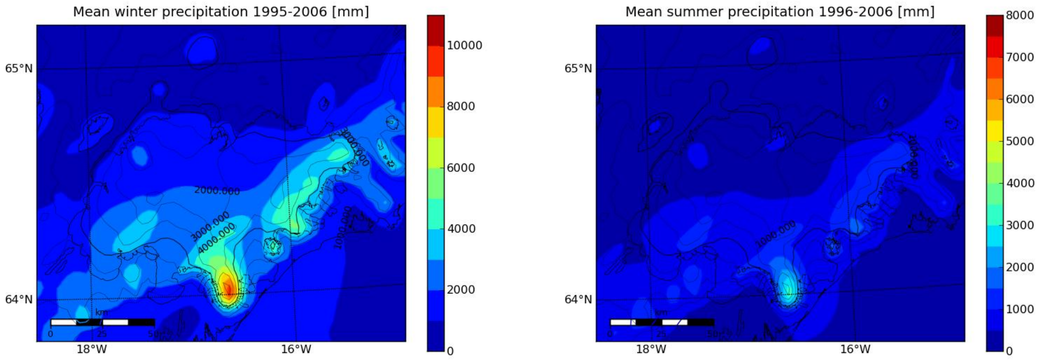

Figure 18. Winter (to left) and summer (to right) precipitation during the time period 1995-2006 for Vatnajökull ice cap and vicinity (source: Institute for Meterological Research).

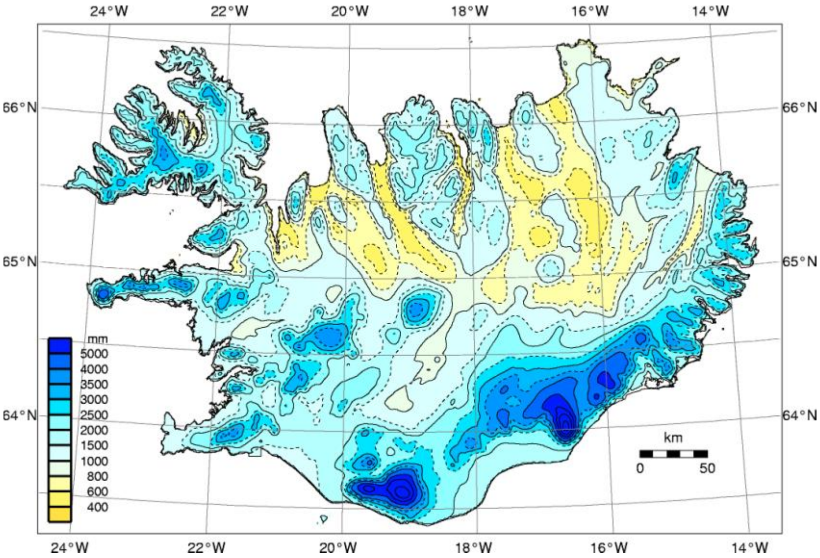

Figure 19. Annual precipitation in Iceland (Crochet et al. 2007).

Temperature

The average temperature of the warmest month, July, exceeds 10°C in the lowlands of southern and western Iceland, but is below that in other parts of the country. This means that most of Iceland belongs to the arctic climate zone. The warmest summer days in Iceland can reach 20-25°C, with winters in Iceland, on the other hand, being generally very mild for this northerly latitude. The coastal lowlands have mean January temperatures close to 0°C, and only in the highlands of central Iceland do the temperatures stay below -10°C. The lowest winter temperatures in northern Iceland and the highlands are generally in the range of -25 to -30°C, with -39.7°C being the lowest temperature ever recorded. The highest temperatures recorded were around +30°C.

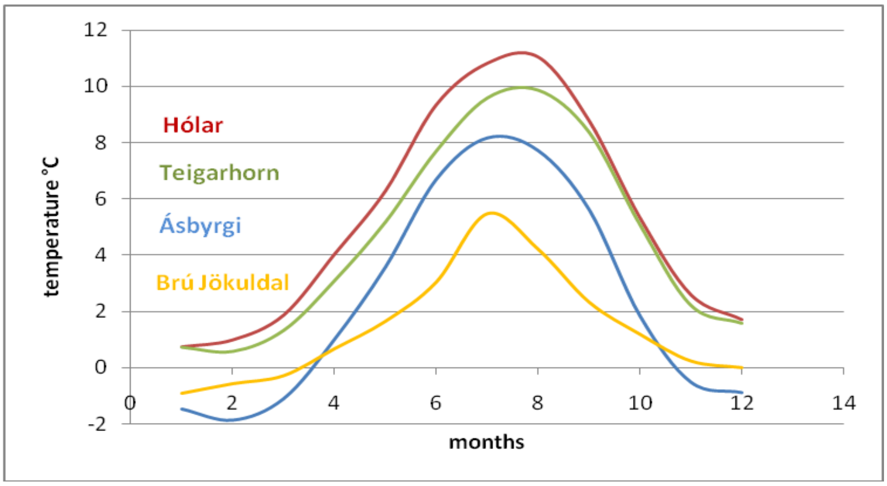

Figure 20. Monthly average temperatures from 4 stations within or near the National Park during the period 2000-2009 (source: portal.belgingur.is).

Summer temperatures in the southern part of the national park range from 10-20°C and the winters are mild, with temperatures even above 0°C, but not much lower than -10°C. Melting even takes place during the winter months in the ablation area of the southern outlets of Vatnajökull (figure y). The temperature is considerably lower in the highlands than on the coast and the frost intensity is also higher.

A föhn wind is a type of dry down-slope wind which occurs in the lee (downwind side) of a mountain range. It is a rain shadow wind, which results from the subsequent adiabatic warming of air which has dropped most of its moisture on windward slopes. As a consequence of the different adiabatic lapse rates of moist and dry air, the air on the leeward slopes becomes warmer than equivalent elevations on the windward slopes. This phenomenon is well known on Vatnajökull and temperature difference can be up to 10°C.

Winds

The dominant wind directions in Iceland are from easterly directions, E, NE-SE, and reflect the passage of cyclones on paths just south of Iceland. Westerly and north-westerly winds are infrequent. Regionally and locally both wind directions and wind speeds are highly influenced by local topography and altitude. Generally, wind speeds are higher in the highlands than the coastal lowlands, but local topography can canalize winds and cause very high winds in some lowland valleys. The highest wind speeds measured in gusts only very rarely exceed 50 m/second. The frequency of storms is highest in the fall and during the winter months. Storm days per year, with average wind speeds exceeding 18 m/second, are generally 10-20 in the lowlands, but at places >50 in the highlands and at exposed outer coastal areas. The large ice caps, Vatnajökull in particular, can generate strong catabatic winds.

Dust storms are very effective in eroding and transporting soil materials, and it has been calculated that more than 10 tons of material can be in motion across every transect meter per hour. In the arid highlands north of the Vatnajökull ice cap, where vegetation cover is sparse and the soils heavily affected by volcanic tephra fallouts, dust storms are very frequent in the summer and early fall.

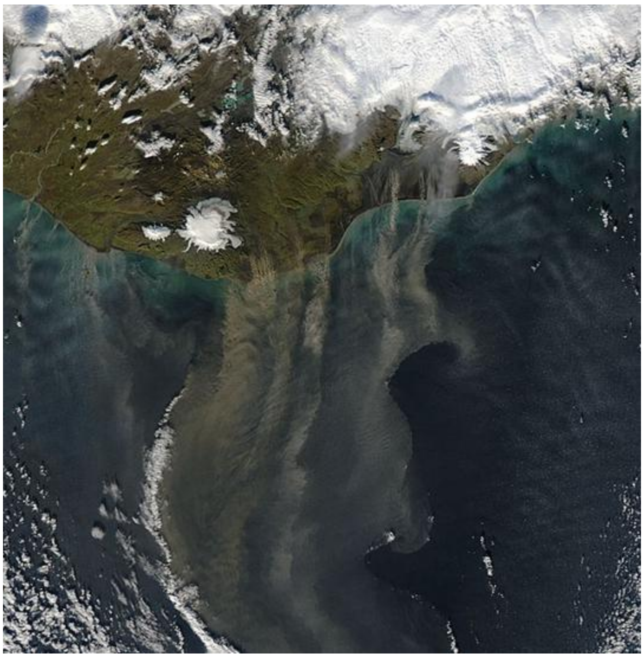

Figure 21. **to the left**: A sandstorm coming from the dry highlands and sandur fields of Southern Iceland, 5th of October 2004. Image courtesy of MODIS Rapid Response Project at NASA/GSFC (satellite image: http://rapidfire.sci.gsfc.nasa.gov/gallery/). **Figure 22. to the right:** A storm from the sandur in front of Dyngjujökull blowing over the northern highlands, reaching Melrakkaslétta and Langanes (http://earthobservatory.nasa.gov/images/imagerecords/).

The winds exhibit great differences in their strengths and frequencies in different regions and at different times of the year. The greatest wind velocities occur during the winter months. Winds are particularly common from the north-east, east and south-east.

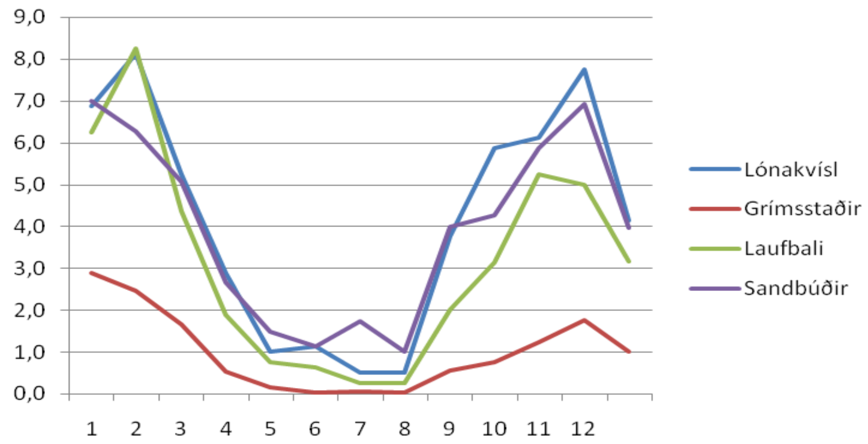

Figure 23. Number of days with wind more than 20 m/s.

Small scale geomorphology

Einarsson, 1994

Glaciers erode, transport, and deposit vast amounts of sediment in the ice, below and on top of the ice, and with glacial rivers, producing loose sediments ranging in size from silt to boulders. In highland areas frost shattering is actively at work breaking down rocks and the crust of lava fields. The freezing of water in the soils produces fascinating landforms, which are common in the highlands. In this chapter we mention a few of the geomorphological processes at work which actively shape the small scale landscapes of the national park.

Figure 24. to the left: Frost weathering on a big boulder in Breiðamerkursandur. **Figure 25. to the right:** Solifluction forming rippled slopes.

Frost activities

During winter the soil gradually freezes and ice is formed. Due to its increasing volume, the soil is lifted upwards. Ice expansion lifts small stones and pebbles, but during thaw these do not return into their original position and the hollows are filled by fine grained material. In this way stones are gradually lifted so that in time a gravel bed covers the ground. Ice expansion not only causes lifting of the soil, it also results in a lateral pressure which causes the soil to push upwards in a hummocky pattern. Repetition of these movements results in hummocky ground on grassy land and stone polygones on unvegetated ground.

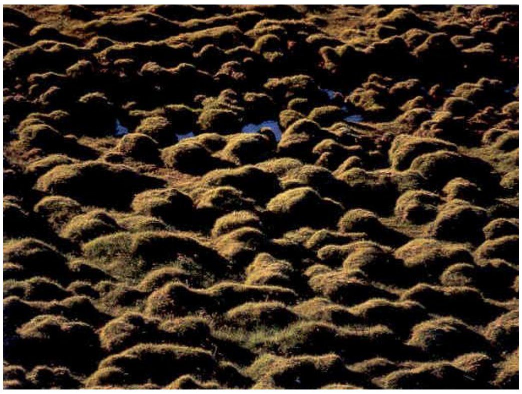

Figure 26. to the left: Hummocky ground. **Figure 27. to the right:** Stone polygons.

Solifluction
In spring the ice melts from above and from below. But the meltwater can only move downwards when the frozen layer beneath is impermeable. The thawed soil becomes saturated and creeps slowly downward on sloping ground. Rippled mountain slopes produced by solifluction are very common in Vestur-Skaftafellssýsla.

Aeolian processes and landforms
Wind has little effect on vegetated land or bedrock but it causes great damage in areas of scant vegetation and where unconsolidated soil is at the surface. The wind swirls dust into the air while sand and gravel roll along the ground tearing up the vegetation and eroding the soil, polishing the bedrock and boulders. In volcanic areas, the wind transports great quantitites of ash and pumice. Wind is therefore an effective tool for erosion. Windborne sand smoothes and polishes rock outcrops making them completely smooth. The wind eroded surface usually points landwards – in the S northwards due to the dry north wind and in the N southwards due to the dry wind from south. The effects of wind erosion depend greatly on the type of rock, so that softer beds are eroded first. These landforms can be seen in the highland areas north of Vatnajökull, and spectacular wind-eroded hyaloclastite cliffs are seen in Dyngjufjöll mountains.

Figure 28. to the left: Sand ripples on Gæsavatnaleið south of Askja. **Figure 29. to the right:** Windblown hyaloclastite ridges in Dyngjufjöll, Mt. Herðubreið in the background (the classic table mountain).

Geo-sites of special interest in Vatnajökull National Park

Þórðarson et al. 2002; www3.hi.is/~arnie/; Baldursson et al. 2003; Benediktsson et al. 2008;Friðleifsson 1992; www.norvol.hi.is; www.jardvis.hi.is; www.ust.is, Carrivick et al., 2004, Evans et al,. 2002; Helgason et al., 2001;Jónsson, 1945; Spedding et al., 2002; Benediktsson et al., 2008; Bennett et al., 2000

Jökulsárgljúfur canyon

Jökulsárgljúfur canyon was carved out in repeated catastrophic jökulhlaups in Jökulsá á Fjöllum originating in Vatnajökull some thousands of years ago. The floods presumably originated subglacially near Bárðarbunga central volcano. The largest flood had a peak of about 500.000 m^3/s. The canyon can be divided into three parts. The southernmost part is a 9 km long, pure canyon with vertical walls that follows fault lines trending north-south. The canyon walls comprise lava flows and sedimentary units with one at the foot of the canyon where two thick lava flows overlie it. Undercutting and collapse of the lava layers, induced by erosion of the sediment unit, resulted in Dettifoss, one of the largest waterfalls in Iceland. The middle part of Jökulsárgljúfur is a 9 km long U-shaped valley with boulder and gravel terraces on both sides. The northernmost part of Jökulsárgljúfur is a canyon with vertical walls and ends in Ásbyrgi. Lavish vegetation thrives in sheltered spots among the regular jointed basalt lava flows. Ásbyrgi is an oval depression bounded up to 100 m high vertical walls on three sides, with an opening facing north. In the middle of the gorge, rises a cliff-bounded island; seen from air Ásbyrgi resembles a horse shoe.

Figure 30. Jökulsárgljúfur canyon, viewed from northwest (photo: nordausturland.is).

Krafla

The Krafla volcanic system (which is outside the national park) consists of a basaltic caldera volcano and an elongate fissure swarm. This fissure swarm is 10 km wide and 100 km long, stretching from Sellandafjall in the south to Öxarfjörður in the north. The Krafla central volcano consists of a huge caldera flanked by basalt lava flows. The volcano is built up from subglacial and subaerial eruptions whereas the caldera was formed in a large explosive eruption. This eruption produced the mixed basalt-rhyolite volcanoes of Hágöng during the most recent interglacial (more than 100.000 years ago). Good representatives of rhyolite table mountains are Hlíðarfjall and Jörundur along the outer margins of the caldera, these were formed in subglacial eruptions 20.000 to 30.000 years ago.

Figure 31. Víti explosion crater in the Krafla area (photo: www.maion.com)

Mývatn
Mývatn (protected area, adjacent to VNP) is a large lake at the edge of the Northern Volcanic Zone. The lake and its outflow (River Laxá) is the most fertile freshwater system in Iceland. Its water wells up in a number of springs on the lake shore. Volcanic activity gives good insight into the process of continental drift and volcanic activity. Craters and volcanoes dominate the landscape, such as Hverfjall (Hverfell), Krafla, and Þrengslaborgir. Strange lava formations are found in the area, such as Dimmuborgir and the pseudocraters of Skútustaðir. The bird life and fishing is extremely rich, as a result of the phosphate rich groundwater, relatively high insolation and optimal water depth for aquatic plants and waterfowl.

Snæfell and Snæfellsöræfi

Figure 32. to the left: Mt. Snæfell seen from (photo: Ívar Örn Benediktsson). **Figure 33 to the right**: Brúardalir (photo: Ívar Örn Benediktsson).

Mt. Snæfell is the highest mountain outside the ice caps (1833 m) and a central volcano made of rhyolite and hyaloclastite. It remains unclear whether the volcano has erupted during postglacial time. Snæfellsöræfi is the plateau around mt. Snæfell, scraped by the outlet glaciers Brúarjökull and Eyjabakkajökull. The area is an important breeding ground for reindeer. To the east of mt. Snæfell are Eyjabakkar, the forefields of Eyjabakkajökull, with

lush vegetation and an important breeding area for geese. The forefield of Brúarjökull (the largest outlet glacier of Vatnajökull) has been affected by repeated surges and consists of a 6-7 m thick sedimentary sequence. The surges are among the largest known, the glacier advances 8-10 km in a few months. Three distinct end moraines, originating from the three last surges, are present in the glacier forefield. Several other glacial geomorphological landforms have been mapped and studied in front of Brúarjökull.

Brúardalir
The bedrock is composed of palagonite formations and lava strata from the latter part of the Quaternary. This plateau is eroded by glaciers and rivers and the area is partially covered with till and sand. The main characteristics of the landscape are low mountain ridges and shallow valleys. Álftadalsfjall is a shield volcano from an interglacial of the Ice Age. Several warm springs are found in the area, but in Laugavallardalur is the only high temperature spring.

Kverkfjöll
Kverkfjöll central volcano is partly subglacial and has one of the largest geothermal areas in Iceland (Hveradalir). Kverkfjöll are the 3rd highest mountain range in Iceland, after Öræfajökull and Bárðarbunga. The central volcano has not erupted often in postglacial time, however there is evidence of large jökulhlaups originating from the volcano. Kverkfjallarani is a several km long system of hyaloclastite ridges with a NE-SW orientation. Within the area are two gorges cut into pillow-hyaloclastite ridge walls. The outwash fan immediately in front of Kverkjökull is the most extensive landform in Kverkfjallarani.


Figure 34. to the left: Jökulsá á Fjöllum and Kverkfjöll (photo: Hrafnhildur Hannesdóttir). **Figure 35. to the right:** Trölladyngja (photo: arctichelicopters.com)

Trölladyngja
Trölladyngja is one of the largest shield volcanoes in Iceland, 10 km in diameter. It rises 600 m above the surrounding lava field. 15 km^3 of lava erupted from Trölladyngja, mostly towards the north, possibly all the way down to Bárðardalur. Other shield volcanoes found in Ódáðahraun are Vaðalda and Urðarháls on Gæsavatnaleið.

Tungnafellsjökull and Vonarskarð
Vonarskarð is in the centre of Iceland, within the Northern Rift Zone, between Sprengisandur and Vatnajökull ice cap, and is comprised of three active central volcanoes. The ice-capped

Tungnafellsjökull central volcano is west of Vonarskarð, and has not erupted in postglacial time. In the centre is the Vonarskarð central volcano with its 8 km wide caldera and active geothermal system. The Vonarskarð volcano is a slightly younger structure than Tungnafellsjökull volcano. The subglacial Bárðarbunga central volcano in northwestern Vatnajökull has produced catastrophic jökulhlaups in postglacial time and hyaloclastite formations found in the eastern part of Vonarskarð. Vonarskarð is rich in rhyolite and geothermal activity has produced beautiful geothermal formations. The area is strongly influenced by glacial action and moraines are found in front of the outlet glaciers of Tungnafellsjökull and on the eastern side of Vatnajökull in Vonarskarð.

Figures 36 & 37: Vonarskarð (photos: Hrafnhildur Hannesdóttir).

Dyngufjöll and Askja

The active volcanic system of Dyngjufjöll extends 100 km to the north from the margin of Vatnajökull ice cap. The Pleistocene formations in Dyngjufjöll are the oldest exposed rocks in the area composed mainly of hyaloclastite forming a massive cluster of mountains. The postglacial history of the area is known from tephrochronological studies and field observations and studies of aerial photographs of lava stratigraphy. The Askja caldera was formed in several eruptions. Askja is one of the largest and most active volcanoes in Iceland. The first well documented eruption in historical time, is the explosive eruption of 1875, which resulted in the formation of Öskjuvatn.

Figure 38. to the left: The Dyngjufjöll volcanic center with the volcanic formations of the Holocene (norvol.hi.is). **Figure 39. to the right:** Askja in Dyngjufjöll (photo: www.fva.is)

Mt. Herðubreið, Herðubreiðarlindir and Ódáðahraun

Ódáðahraun is the greatest lava expanse in Iceland, about 5,000 km^2 in size, and is divided by the northern volcanic zone. Rough, sand-strewn lava fields are characteristic for the area. Mt. Herðubreið is a classic table mountain, with a lava cap protecting the hyaloclastite formations. It is the national mountain of Iceland and can be seen from far away, from the north, south, east and west. Herðubreiðarlindir is one of the few oases in the middle of the deserted Ódáðahraun. The area is dry due to the rain shadow of Vatnajökull and the permeable lava fields. Lush and species-rich vegetation and birdlife characterize Herðubreiðarlindir. Along Jökulsá á Fjöllum, jökulhlaup sediments (from sand to huge boulders) cover the bedrock and have in some places polished the surface.

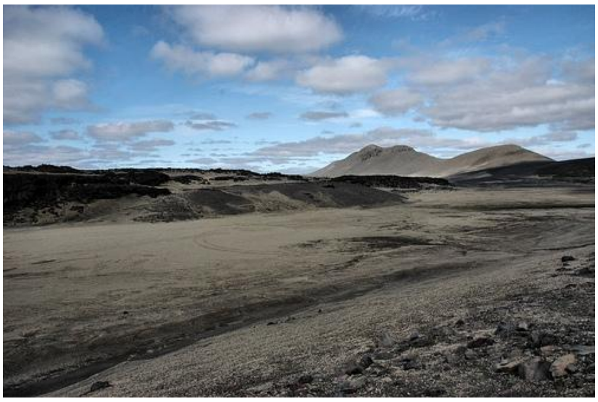

Figure 40. on the right: Mt. Herðubreið seen from Herðubreiðarlindir, jökulhlaup boulders in the forefield (photo: Hrafnhildur Hannesdóttir). **Figure 41. on the left:** Glimpse of Ódáðahraun (photo: www.farm4.static.flickr.com).

Veiðivötn

Many volcanic and tectonic features with SW lineament are recognized in this region, which borders on the west side of Vatnajökull. Those include: crater rows, single craters, cinder cones, faults, fissures, rift valleys, hyaloclastite ridges and mountains, pillow lava sheets along with many lakes. Here we find the Tröllagígar craters which were formed during the latest eruption in the system, between 1862-1864 AD, and produced the Tröllahraun lava sheet. This is where we also find the great rift valley Heljargjá, the mountain Þóristindur (826m) and the extremely long volcanic fissure Vatnaöldur which prides itself with a beautiful lineament of craters and cinder cones formed in 870 AD. The cinder cones Máni, Fontur and Saxi in the vicinity of Heljargjá rift valley were probably formed in the early Holocene. Gravity measurements show that the cinder cones are part of a crater row, not unlike those seen in the Vatnaöldur fissure, which has been buried beneath 50-100 m thick lava in Heljargjá valley. The craters found in the Veiðivötn lakes were formed during the last major eruption in the fissure swarm in 1477 AD. All lavas originating from the Veiðivötn fissure swarm have common chemical composition of thoelitic basalt.


Figure 42. to the left: Lakes within the Veiðivötn volcanic system (www.isafoldtravel.is). **Figure 43. on the right:** Ófæruoss í Eldgjá (photo: www.hotelskogar.is).

Laki

The Skaftá fires in 1783-1784 (Skaftáreldar) was the largest eruption since settlement in Iceland and the accompanying lava flow is the third largest on earth in postglacial time. The tephra fall had devastating effects on the inhabitants and farming practices. Farms were covered by the lava flow or had to be abandoned due to immense amounts of toxic tephra. The Lakagígar crater row sits on 10 parallel fissures, each of which is 2–5 km long. A total of 135 craters were formed during the eruptive phase. Two lava streams flowed down to the lowlands, the Eldhraun (the western flow) and Brunahraun (the eastern flow). Together they cover 0.5% of the area of Iceland.


Figure 44. on the left: Lakagígar (Laki craters) where the eruption took place in 1783-1784 (photo: norvol.hi.is). **Figure 45. on the right:** Moss covered Eldhraun in Vestur-Skaftafellssýsla (photo: www.si.smugmug.com).

Eldgjá
The Eldgjá vents (outside VNP) form a discontinuous 75 km long volcanic fissure extending from the Katla volcano in the west to the tip of Vatnajökull in the east. This old tectonic graben was reactivated in the 934-40 eruption (Þórðarson et al., 2002). The Landbrotshólar cone group was formed by rootles eruptions when the Eldgjá lava advanced onto the marshy coastal plains in front of the Síða scarp. With an extend of 60 km^2 it is the largest cone group in Iceland. Whereas a big part is buried beneath the 1783 Laki lava flow which has covered around 150 km^2 (Þórðarson et al., 2002).

Fjaðrárgljúfur and Kirkjugólf
The Plio-Pleistocene strata that form the old seacliffs above Kirkjubæjarklaustur (outside VNP) consist of a 700 m thick volcanic succession of the Síða Group. This was formed before the Ice Age and is dominated by 14 large volume subaqueous hyaloclastite lava flows. Each flow sequence is typically capped by a 15 m thick unit of well-bedded lapilli tuff. The lava at the base of these flows often show columnar joints, such as those forming the pavement like Kirkjugólf at Kirkjubæjarklaustur and the cliffs of Dverghamrar (Þórðarson et al., 2002).

In the past 10.000 years the rivers have cut many gorges and gullies into the Síða highlands, but none as spectacular as the Fjaðrárgljúfur gorge. Here the Fjaðrá river has carved out a 100 m deep ravine into the hyaloclastite flows and other formations of the Síða (Þórðarson et al., 2002).

Skaftafell
The geological history of Skaftafell spans the last 5 million years. In the beginning the land was mainly made up of lavas. The Quaternary started about 2.7 million years ago, when alternating glacial and interglacial periods affected the landscape. Subglacial volcanic eruptions formed hyaloclastite ridges. The glaciers draining Öræfajökull have carved out deep valleys, most of them reaching 200 m below sea level. Frontal lakes have started to form in front of most of the valley glaciers in Skaftafell and will grow as glacier retreat continues.

Figure 46. Öræfajökull seen from Skaftafellsjökull with Hafrafell (hyaloclastite ridge) in the foreground. **Figure 47. to the right:** Skaftafellsjökull and Svínafellsjökull outlet glaciers, separated by Hafrafell (photo: www.frostandfire.is).

Lómagnúpur
Lómagnúpur is almost 700 m high and features the highest cliff face in Iceland. The cliff was carved out by glaciers and later modified by coastal erosion. Late in the 18th century a large landslide fell from the cliff, reaching several hundreds of meters out on the sandur plain, leaving scattered boulders and angular rocks down below. Another landslide occurred in 1998.

Figure 48. to the left: Lómagnúpur from the east on Skeiðarársandur (photo: www.icelandicphotos.net). **Figure 49. to the right:** The Svínafell layers crop out at the base of the mountain, seen from the west (photo: www.travel.webshots.com).

Grímsvötn

The subglacial Grímsvötn central volcano is located in western Vatnajökull and is the most active volcanic system in Iceland. In the last 800 years at least 60 eruptions are known, most of them originating in the Grímsvötn caldera. Radio-echo sounding measurements have revealed the bedrock topography of the volcano and it rises 700-900 m above the surrounding bedrock. The central volcano is 15 km in diameter and is a caldera composed of 3 smaller calderas. In the last 15 years three eruptions have taken place in Grímsvötn; the Gjálp eruption in 1996, followed by the Grímsvötn eruptions in 1998 and 2004.

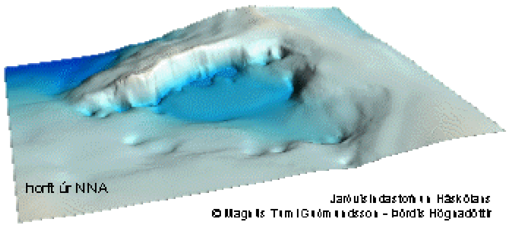

Figure 50. to the left: Grímsvötn caldera in 2010 (photo: Hrafnhildur Hannesdóttir). **Figure 51. to the right:** 3-D image of Grímsvötn (photo: www.jardvis.hi.is).

The Svínafell layers

The Svínafell layers are a 120 m thick lacustrine sedimentary sequence at the root of Öræfajökull volcano. The sediments are about 500,000 years old, and contain fossils, primarily leaves, that record climate changes in Iceland through the Pleistocene. These are the youngest remains of the deciduous broad-leaved forest, which characterized the Tertiary flora of Iceland. Fossils of birch, blueberry bushes, crow berry bushes, mountain ash, willows, ferns and other plants.

Esjufjöll

Esjufjöll central volcano is part of the volcanic side-belt stretching from Snæfell central volcano in the north and Öræfajökull central volcano in the south. The subglacial Esjufjöll volcano is within Breiðamerkurjökull. Most of the volcano, including the 40 km^2 caldera, is covered by the ice cap. Parts of the SE flank of the volcano are exposed, and species-rich vegetation occupies these isolated nunataks.

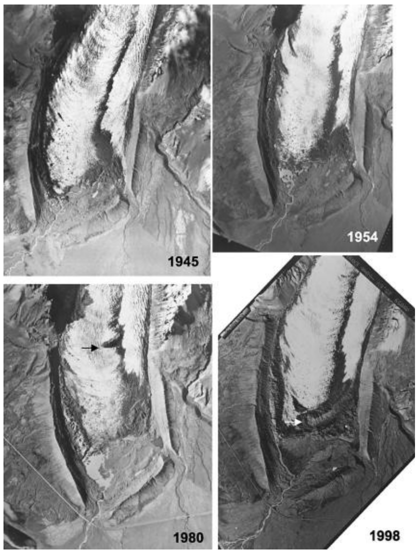

Figure 52. to the left: Esjufjöll in Breiðamerkurjökull (photo: María Ingimarsdóttir). **Figure 53. to the right:** Kvíárjökull 1945, 1954, 1980 and 1998 (photo: Landmælingar Íslands).

Kvíárjökull

Some of the most remarkable end moraines are located in front of Kvíarjökull, an outlet of Öræfajökull. An arcuate 100 m high moraine ridge encircles the terminus, forming the highest moraines in Iceland. The ridge is a composite feature, initiated ca. 3200 BP, and built up during several episodes of re-advances of the glacier during the Holocene. At times of greatest climatic deterioration, the ridge has acted to constrain growth of the glacier preventing its lateral expansion to form a piedmont-style snout and possibly also restricting its forward advance.

Breiðamerkurjökull, the sandur and *Jökulsárlón*

Breiðamerkursandur is the outwash plain of the surge-type outlet glacier Breiðamerkurjökull. It is one of the largest sandurs in Iceland, comprised of moraines, drumlins, eskers and other glacial geomorphological small-scale features. Breiðamerkurjökull is the second largest outlet glacier of the southern margin of Vatnajökull with well-developed medial moraines. The nunataks of Esjufjöll and Mávabyggðir feed debris to the glacier to produce medial moraines. The glacier reached its maximum extent in historical times during the latter half of the 19th century (the Little Ice Age maximum). During the settlement period of Iceland from AD 874 to AD 930 the outlet glaciers of southern Vatnajökull are thought to have been tens of km behind their present margins.

As Breiðamerkurjökull and Fjallsjökull (its neighbouring outlet) have receded from their Little Ice Age maximum positions they have uncovered large depressions in which the lakes Fjallsárlón, Breiðárlón, Jökulsárlón and Stemmulón have evolved. Because of the lakes short life-time, glacilacustrine sediments and shorelines are not widespread although some extensive shoreline fragments document the evolution of Jökulsárlón. The glacial lake Jökulsárlón (outside the national park) has increased greatly in size since it formed in the 1930´s. The lake is connected to the sea, hence tides affect the level of the lake and the circulation within the water body.

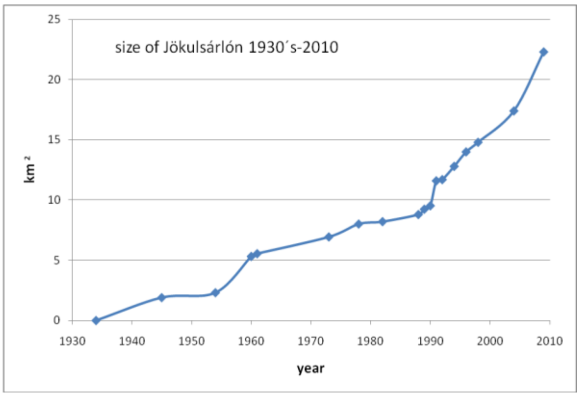

Figure 54. to the left: Jökulsárlón glacial lake has increased in size since it formed in the 1930´s (source: Earth Science Institute, University of Iceland). **Figure 55. to the right:** Push moraines of Breiðamerkurjökull (photo: Evans, 2002).

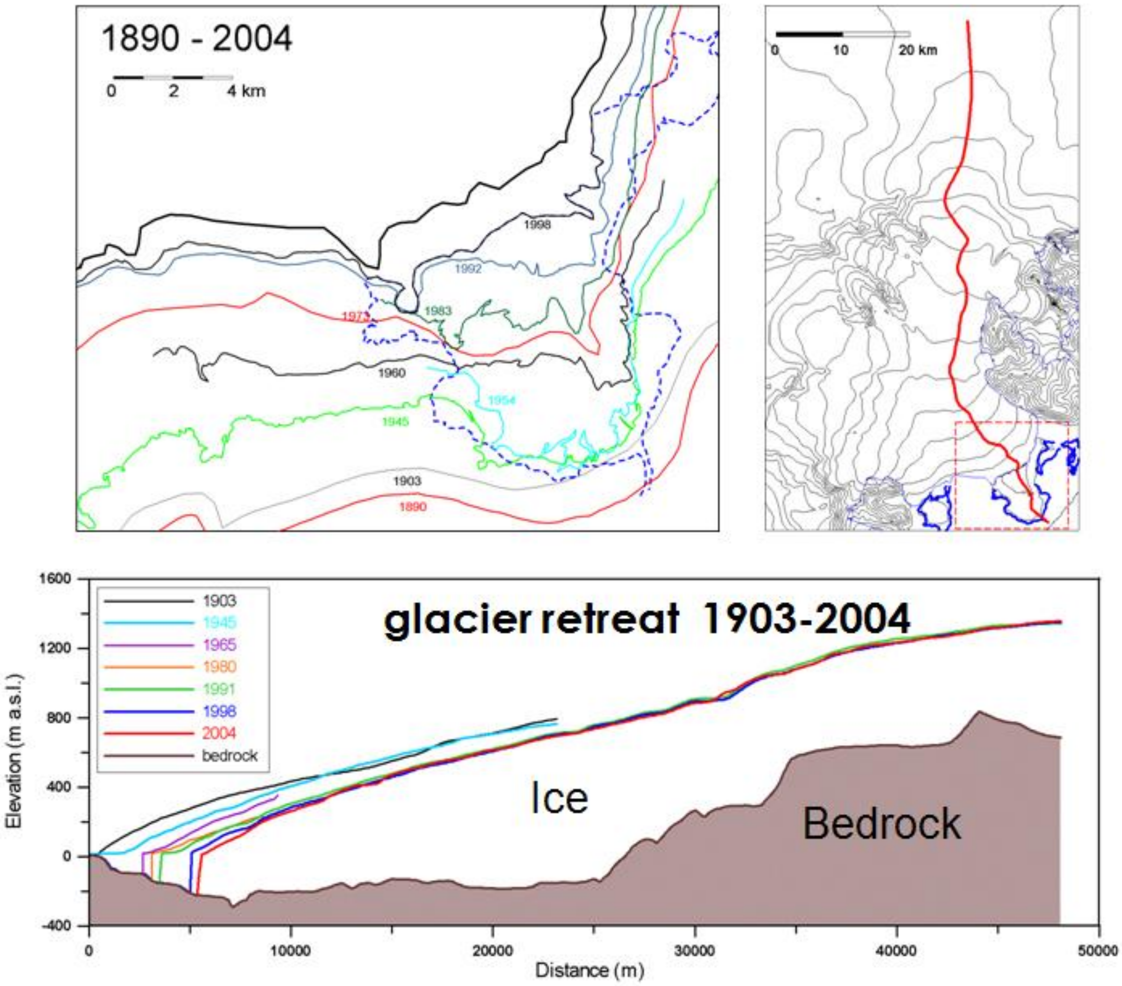

Figure 56. Evolution of Breiðamerkurjökull and Jökulsárlón since the Little Ice Age maximum (source: Earth Science Institute).

Heinabergsjökull and ice-dammed lakes

The Heinabergsjökull outlet glacier, which drains southeast from Vatnajökull ice cap, has been associated with ice-dammed lakes and destructive jökulhlaups for the last 100-200 years. The 7 km long Heinabergsdalur was blocked by the snout of the glacier until just after 1928, forming lake Dalvatn. A total of 8 raised shorelines extend approximately 3 km up-valley,

witnessing the former ice-dammed lake. The ice-dammed lake of Vatnsdalur has decreased in size due to the thinning of the glacier, but it was at its maximum size in the end of the 19th century. At that time the glacier was too thick for the water to break through. As the glacier retreated, repeated jökulhlaups have drained the lake, causing devastating effects on the farms in the forefield of the glacier.

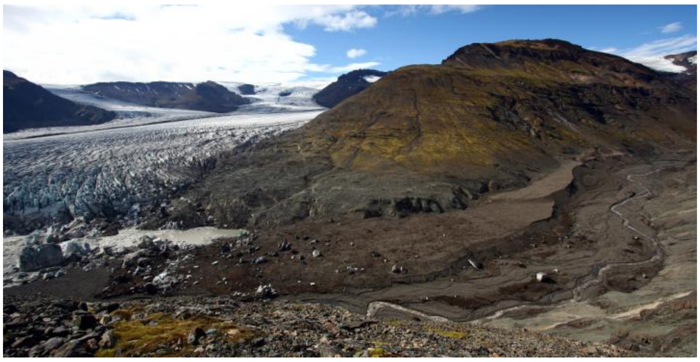

Figure 57. to the left: Vatnsdalur in 2007 (photo: Hrafnhildur Hannesdóttir). **Figure 58. to the right:** Heinabergsjökull and its frontal lake (photo: www.rikivatnajokuls.is).

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